Cold Spray Aluminum for Magnesium Gearbox Repair

Phillip F. Leyman
US Army Research Laboratory
Weapons & Materials Research Directorate

SERDP/ESTCP Surface Finishing Workshop
February 26-28, 2008

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **FEB 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Cold Spray Aluminum for Magnesium Gearbox Repair**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U. S. Army Research Laboratory,Weapons & Materials Research Directorate,Aberdeen Proving Ground,MD,21005**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Surface Finishing and Repair Issues for Sustaining New Military Aircraft Workshop, February 26-28, 2008, Tempe, AZ. Sponsored by SERDP/ESTCP.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**42**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

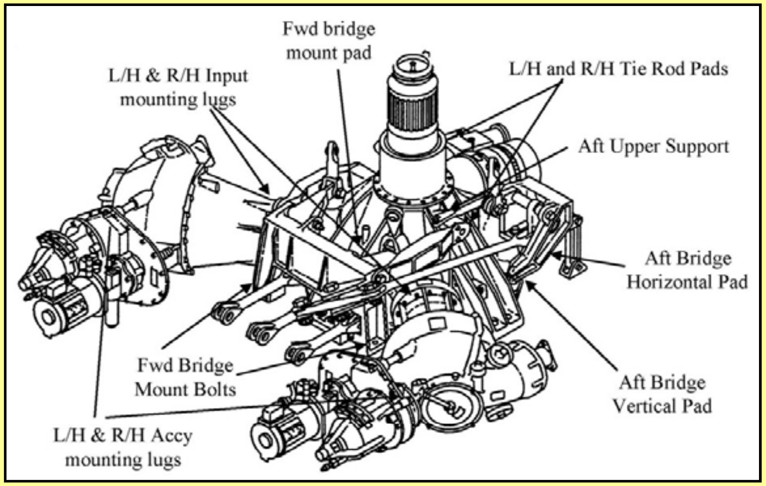
ESTCP Program Goal

ESTCP Proposal 06-E-PP3-031

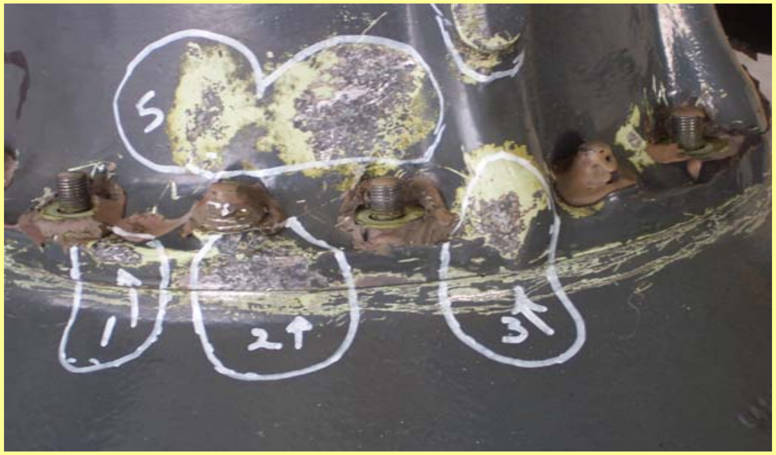
- **To reclaim Magnesium alloy components on Army and Navy helicopters that have been removed from service due to severe corrosion and/or wear.**
- **ARL will provide a repair/rebuild Cold Spray procedure for scrapped parts and assist in the transition and implementation of this technology, initially, at NADEP, Cherry Point, NC.**

Problems With Current Surface Treatment Methods

- Exposure to hexavalent chrome is hazardous to workers' health. OSHA limits on chromium exposure are becoming increasingly stringent.
- Even with chromated surface treatments, Mg components suffer severe degradation in service
- Most corrosion occurs at mating pads, supports, and mounting lugs where dissimilar metal is in contact with Mg; damage is most likely to occur in those locations as well



H-60 Main Transmission Housing showing areas most susceptible to corrosion



Corrosion on H-53 Tail Gearbox Housing

Program Objectives

- Develop the densest, thinnest, most corrosion resistant Aluminum-based Cold Spray coating with the greatest adhesive bond strength to Magnesium.

- Determine effects of feedstock material and process parameters on coating thickness, microstructure, adhesion, and corrosion performance for the Cold Spray coatings on Magnesium substrates.

Joint Test Protocol (JTP) has been developed

U.S. DEPARTMENT OF DEFENSE
Environmental Security Technology Certification Program (ESTCP)

JOINT TEST PROTOCOL

Supersonic Particle Deposition Technology for Repair of Magnesium Aircraft Components

Date: October 2, 2006

Prepared By:
Hard Chrome Alternatives Team (HCAT)

HCAT
SPONSORED BY ESTCP ★ JG-PP ★ PEWG
HARD CHROME ALTERNATIVES TEAM

ARL Leveraged Formal Programs

Develop aluminum cold spray coatings for aluminum, magnesium and/or steel substrates have been established with the following:

1. **Defense Science & Technology Organization (DSTO)**
2. **Joint Strike Fighter (JSF)**
3. **National Center for Manufacturing Sciences (NCMS)**
4. **Lockheed Martin**
5. **Penn State Applied Research Laboratory**
6. **Lawrence Livermore National Labs (LLNL)**
7. **South Dakota School of Mines (SDSM)**

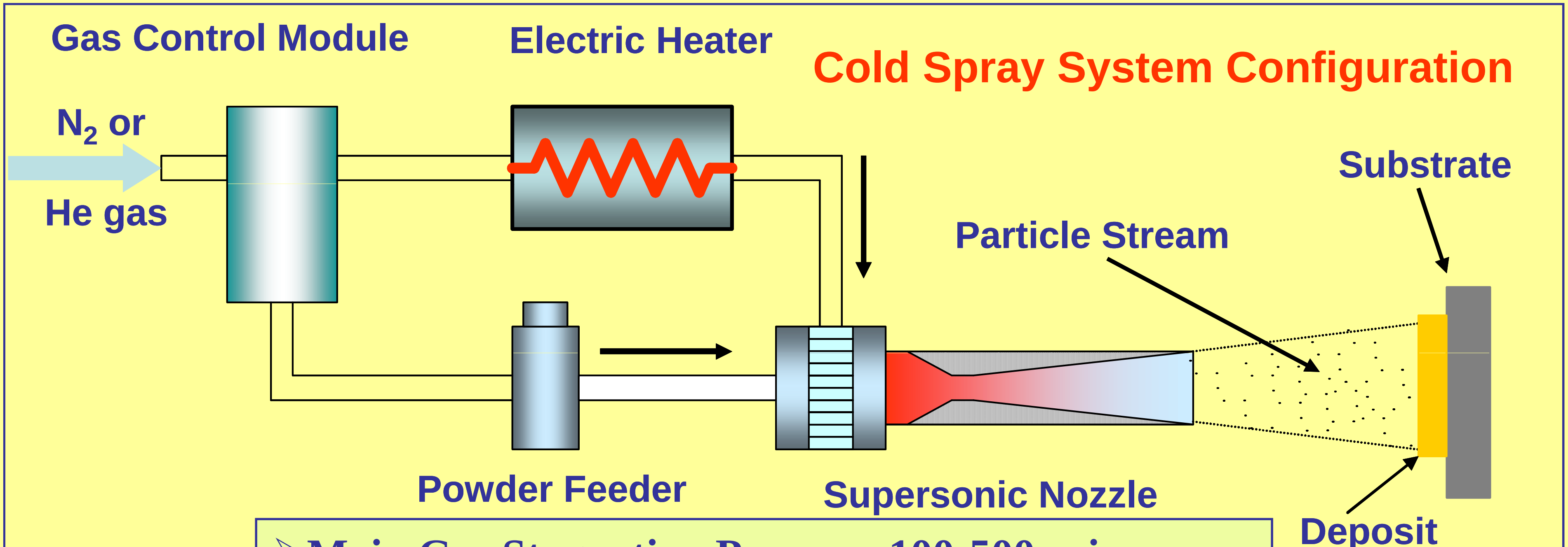
Cold Spray Center at the
US Army Research Laboratory (ARL)
Aberdeen Proving Ground, MD 21005-5069

ARL Cold Spray Research Team

Victor Champagne	Team Lead	(410) 306-0822
Phillip Leyman	Process Engineer	(410) 306-0818
Dr. Dennis Helfritch	Modeling/Simulation	(410) 306-1928
Dr. Matthew Trexler	Materials Engineer	(410) 306-1592
Michael Lister	Materials Engineer	(410) 306-0808
Carl Paxton	Process Technician	(410) 306-2026
Marc Pepi	Mechanical Engineer	(410) 306-0848

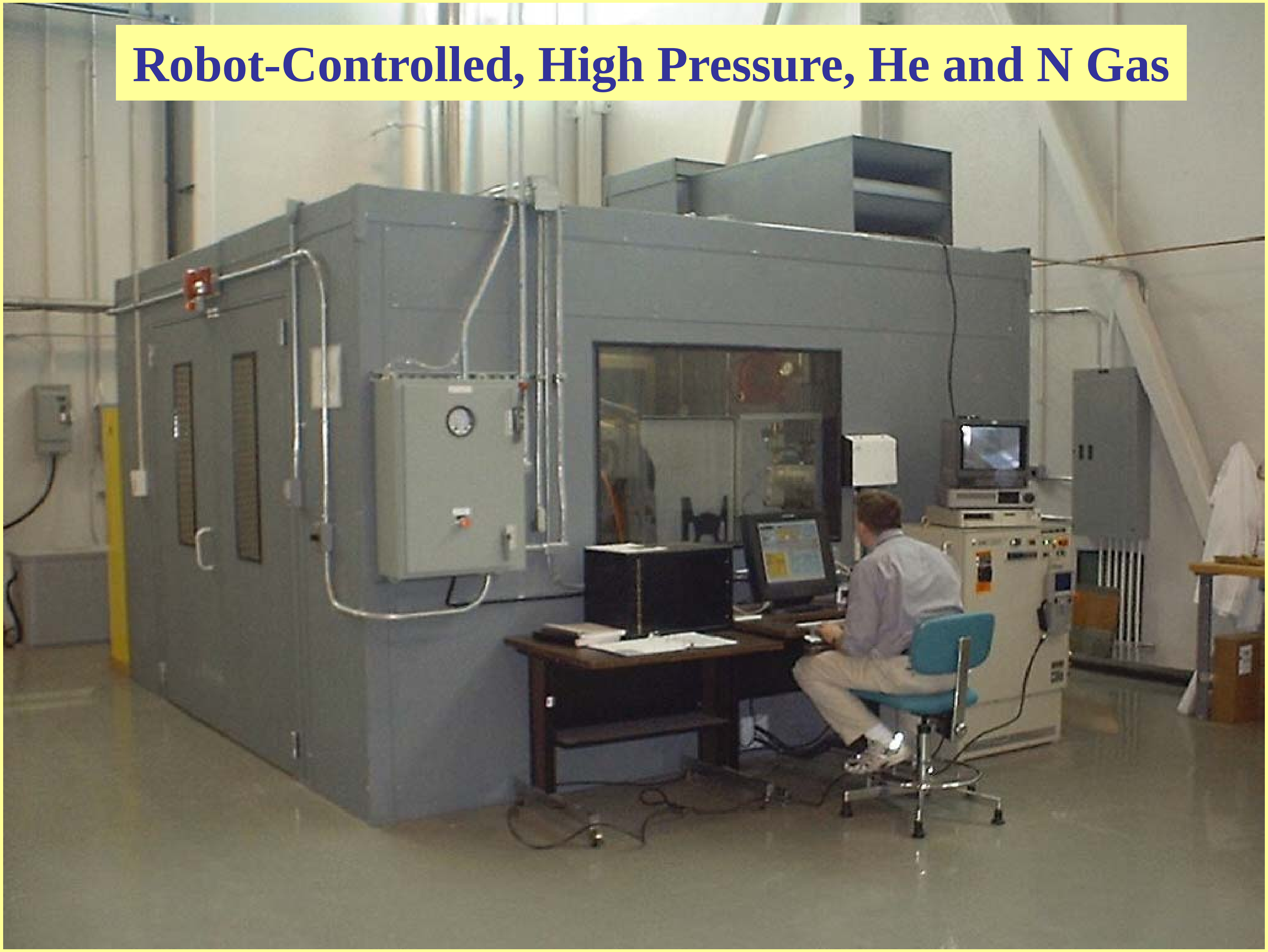
Overview of Cold Spray Technology

Cold Spray: a process by which particulates are deposited by means of ballistic impingement upon a suitable substrate at super sonic velocities to form a coating or a free-standing structure.



- Main Gas Stagnation Pressure 100-500 psi
- Gas Temperature 0-500ºC
- Main Gas Flow Rate 30-100 CFM
- Powder Feed Rate 1 to 10 pounds/hour
- Particle Velocity 300-1500 m/sec.
- Particle Size 1-100um diameter

Stationary Cold Spray System at ARL



Cold Spray Advantages

Mechanical mixing bond at substrate interface

- plastic deformation may disrupt thin oxide surface films to permit bonding
- similar to explosive welding

Compressive residual stresses

- particles "peen" surface
- plasma and wire-arc thermal spray coatings tend to be in tension

High density

- low porosity: < 0.5 %
- low oxide content <0.3%

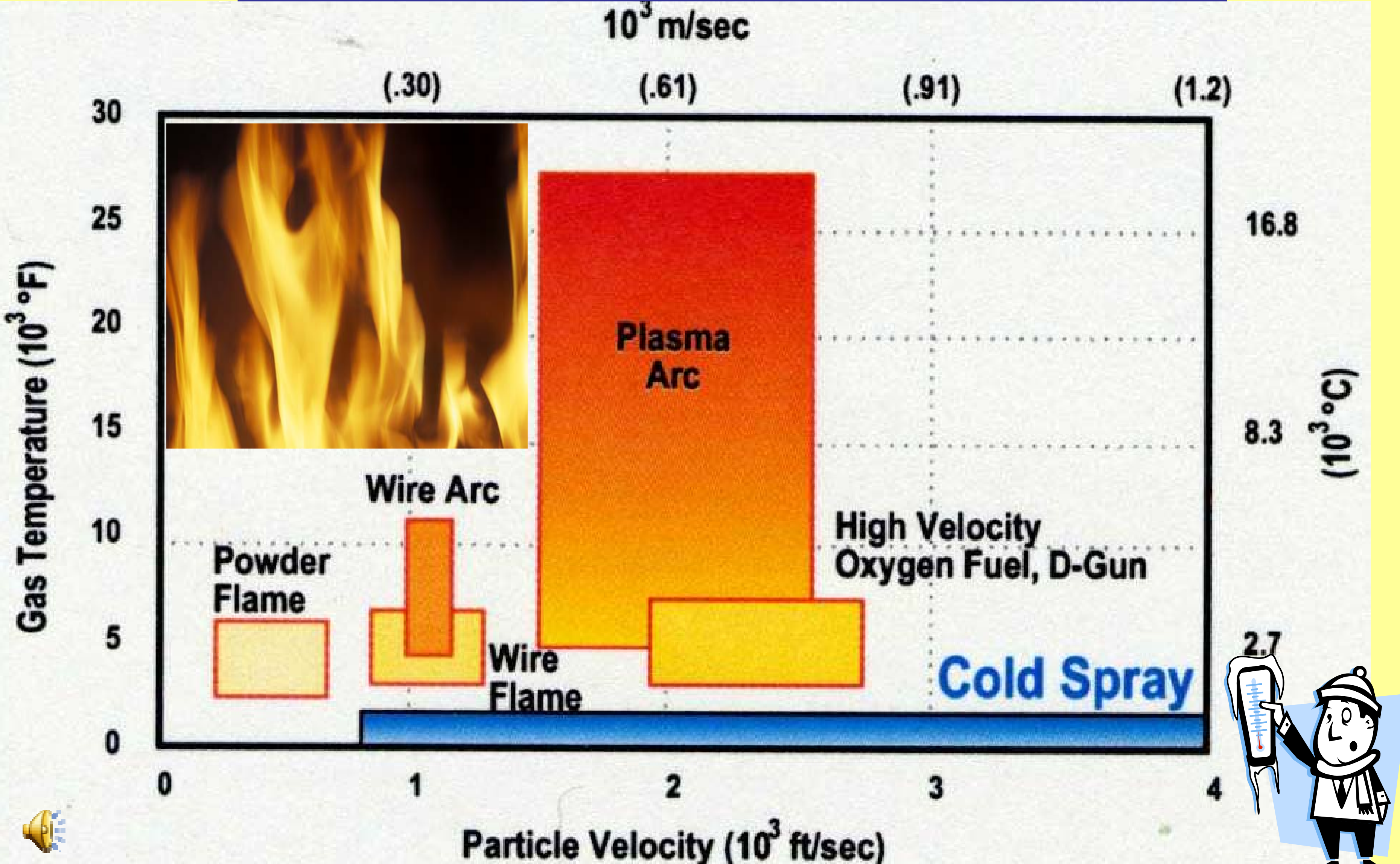
Thick coatings

- free-form fabrication

Low Temperature Application

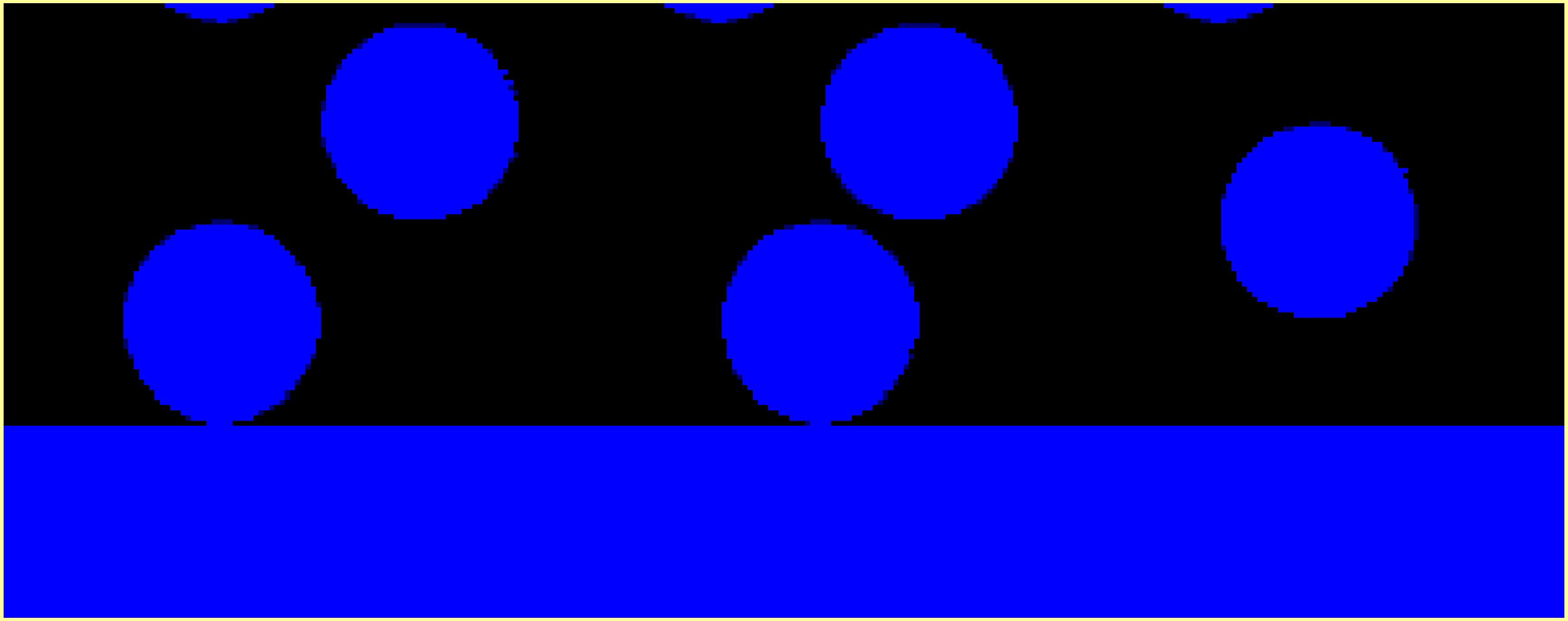
- thermally sensitive substrates
- low stresses due to CTE mismatch

Cold Spray vs. Thermal Spray



Cold Spray is performed at lower temperatures at high particle velocities

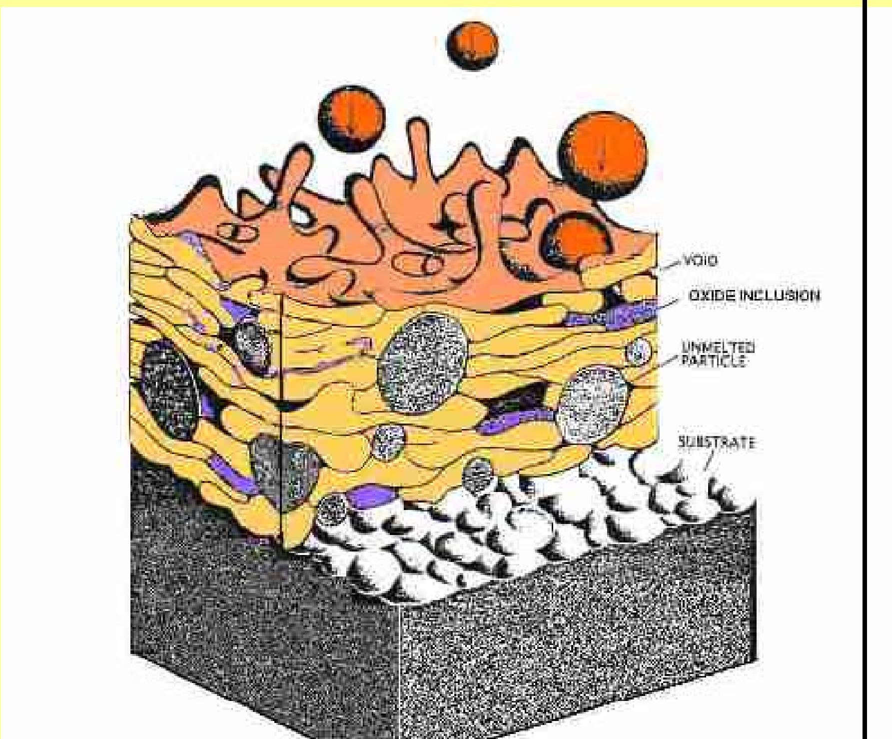
Particle/Substrate Interaction*



*from H. Assadi, www.modares.ac.ir/eng/ha10003/CGS.htm

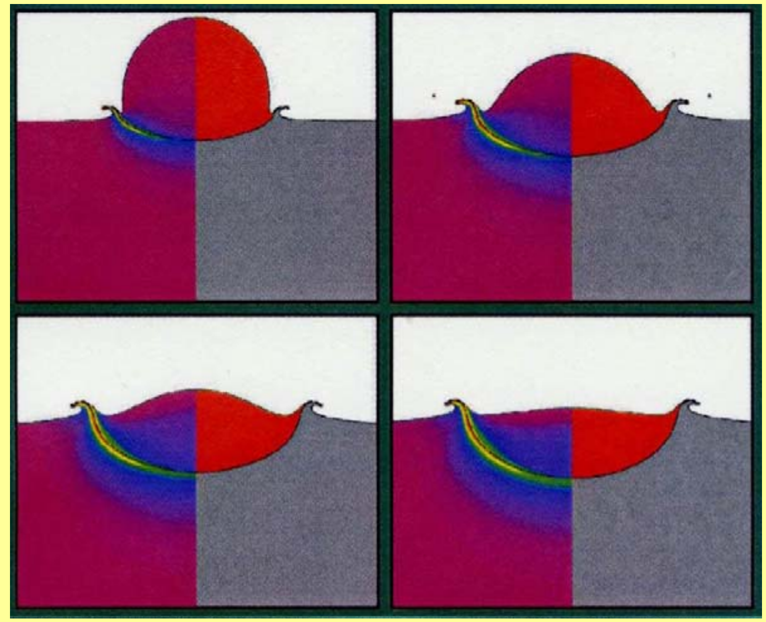
Advantages of Low Temperature Process

Thermal Spray



www.gordonengland.co.uk

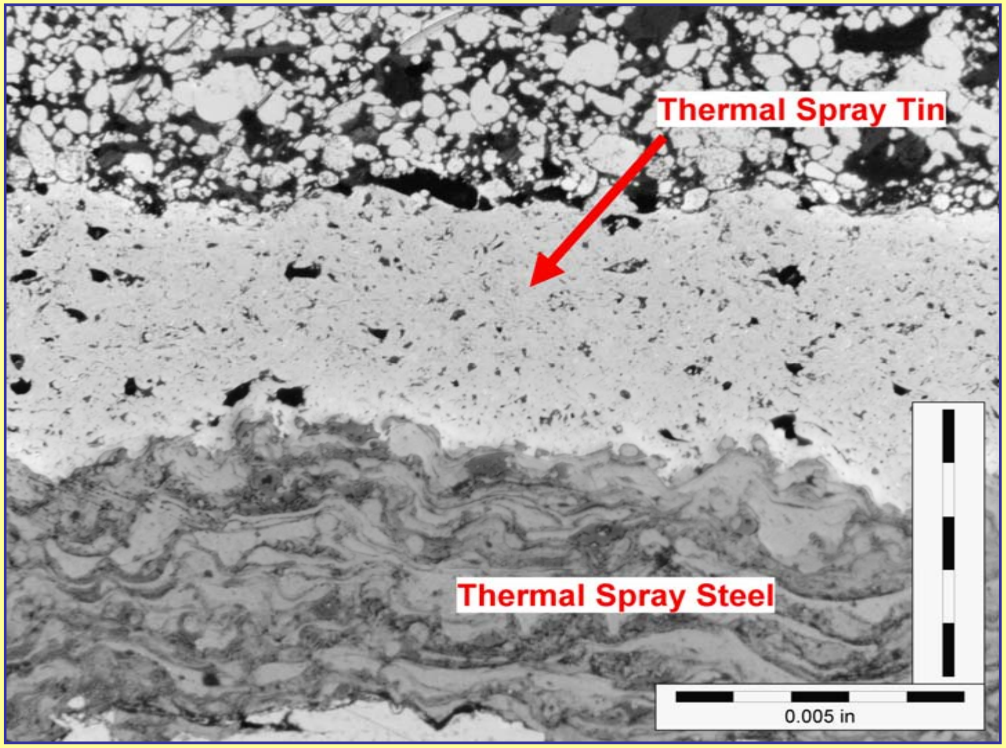
Cold Spray



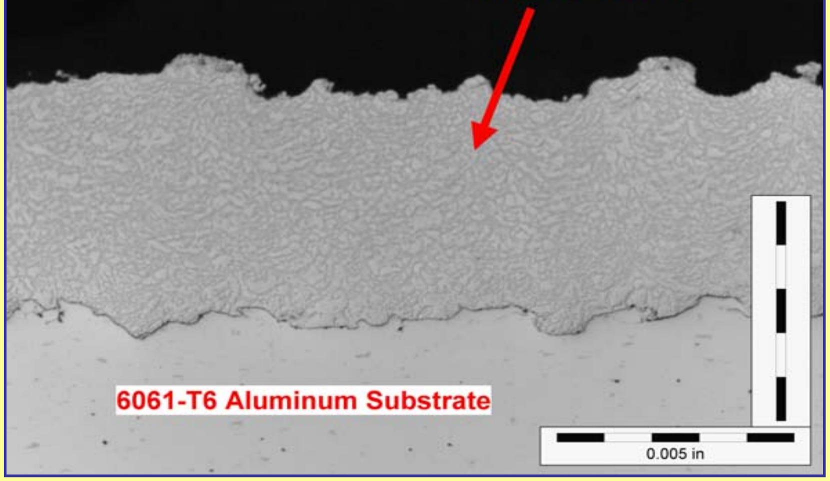
The melting of particles that occurs during most thermal spray processes can result in oxidation of both the coating and substrate materials. The resulting oxides decrease the adhesive and cohesive strengths of the coating. The cold spray process avoids such reactions.

Cold Spray vs. Thermal Spray

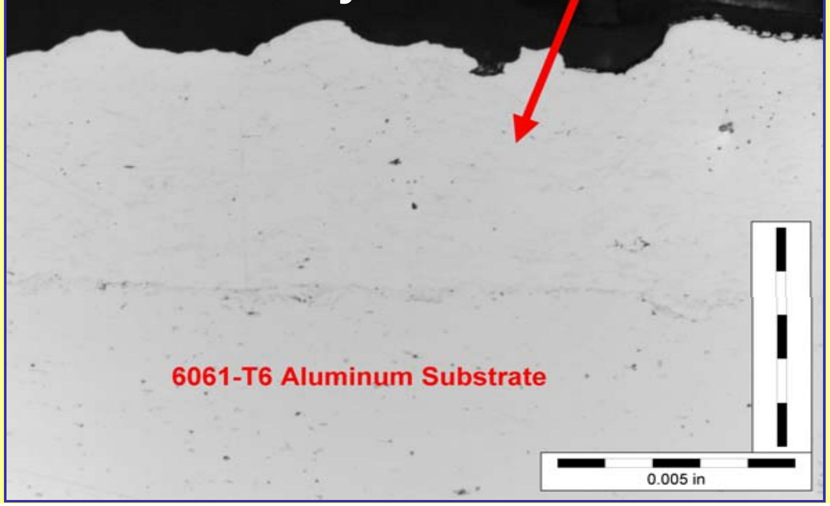
Flame Spray Sn & Steel Coating, 12.2% Porosity



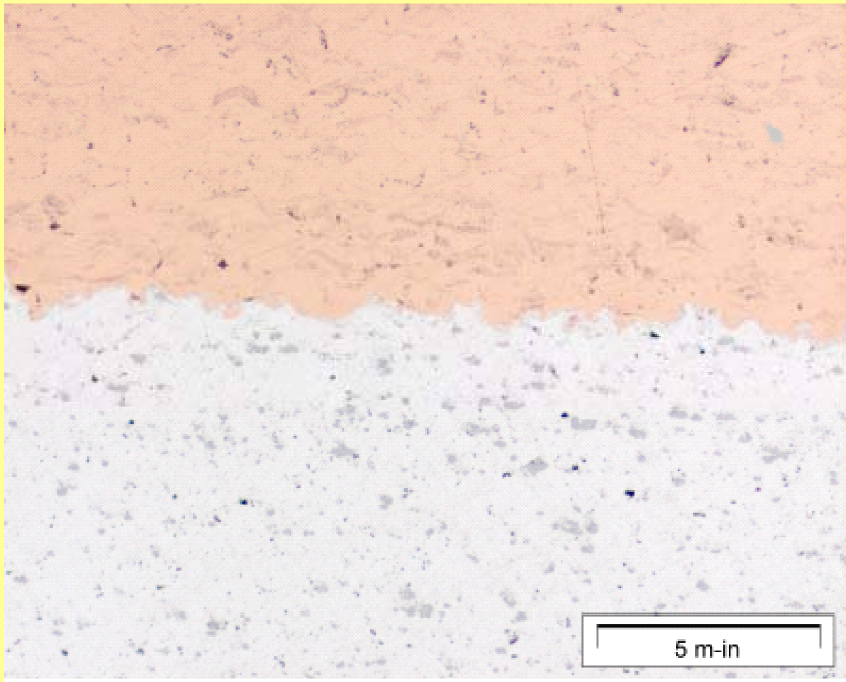
Cold Spray Sn Coating, 0% Porosity

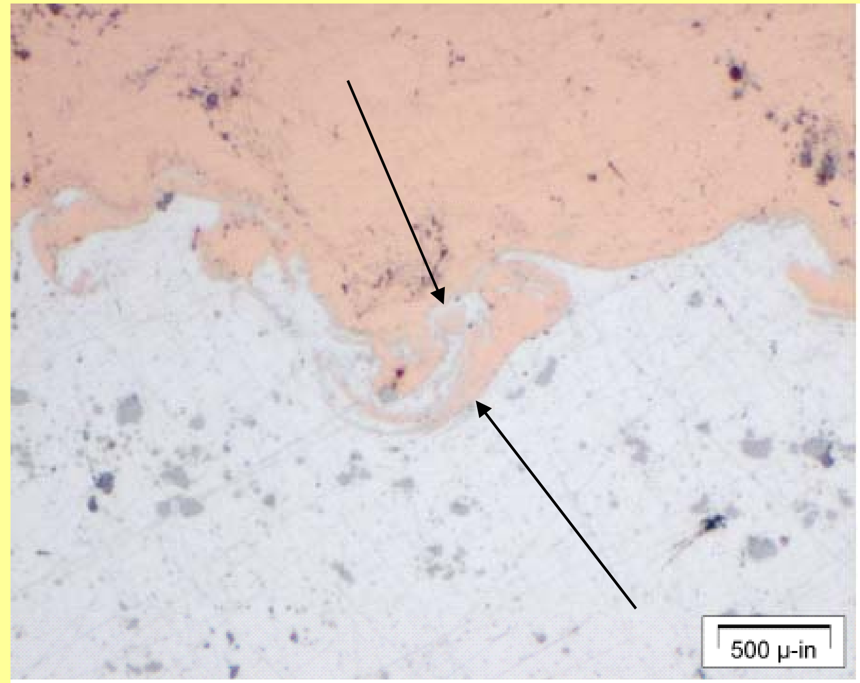


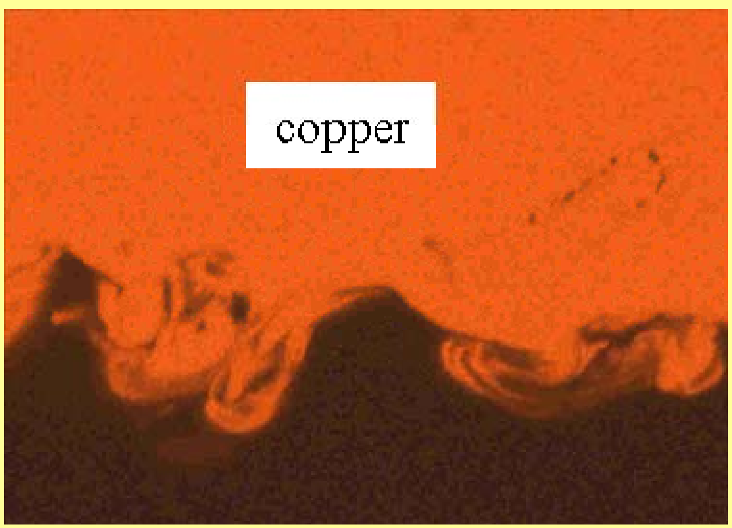
Cold Spray Al Coating, 0.83% Porosity



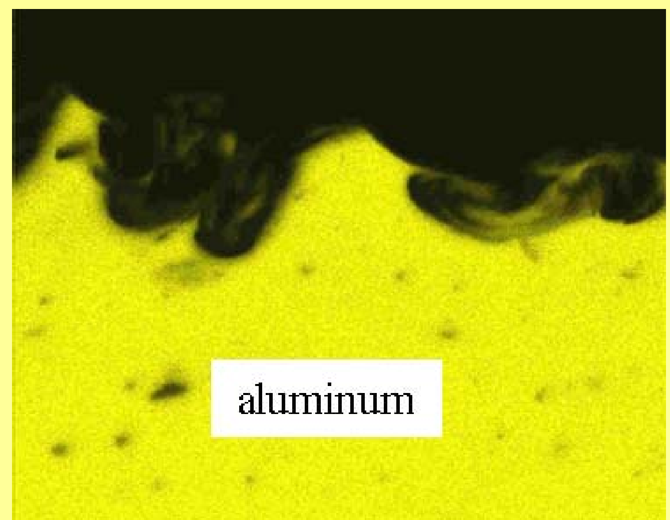
Mechanical Mixing at Interface



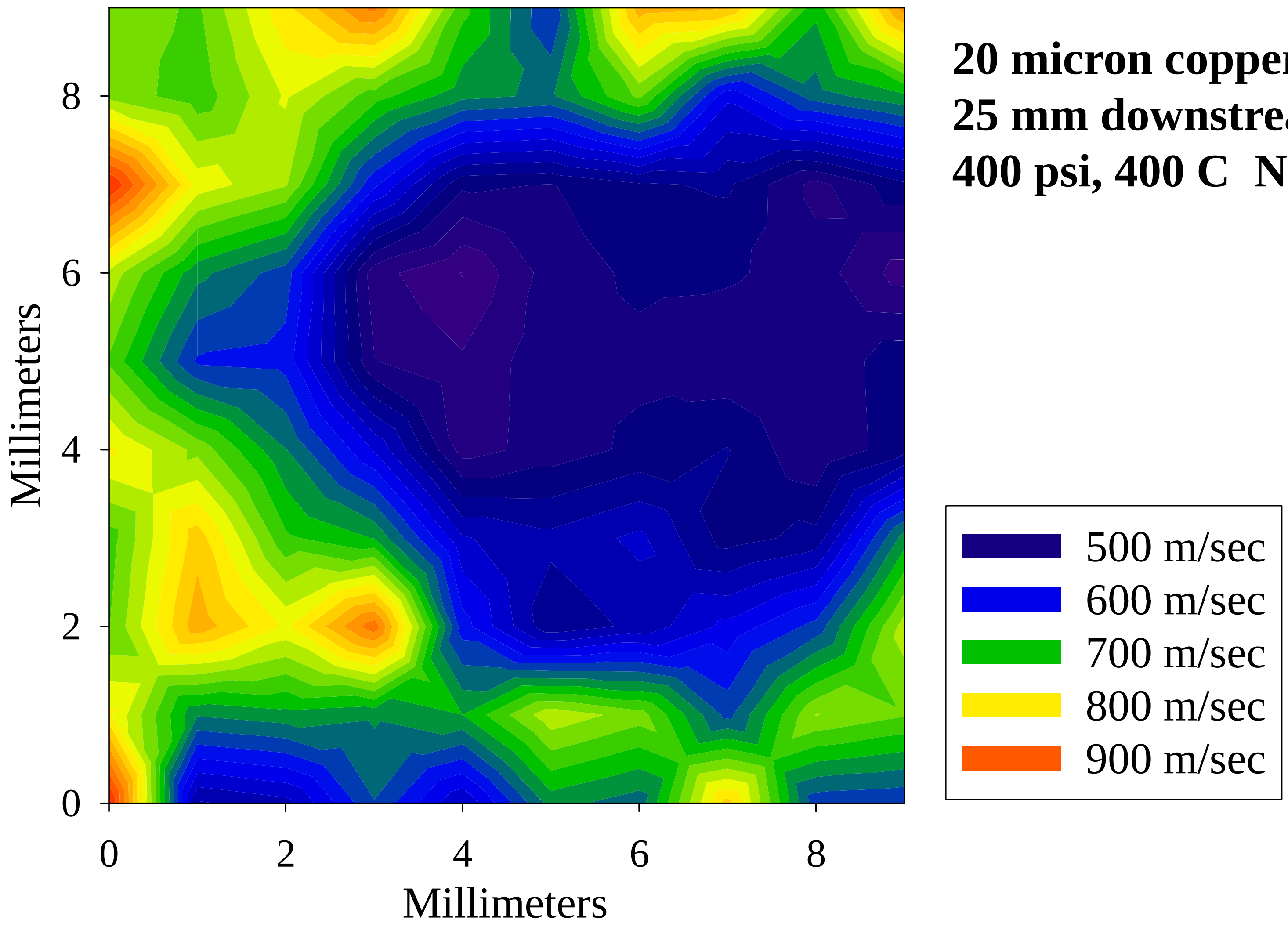




EDS X-ray Mapping showing mechanical mixing between coating material and substrate



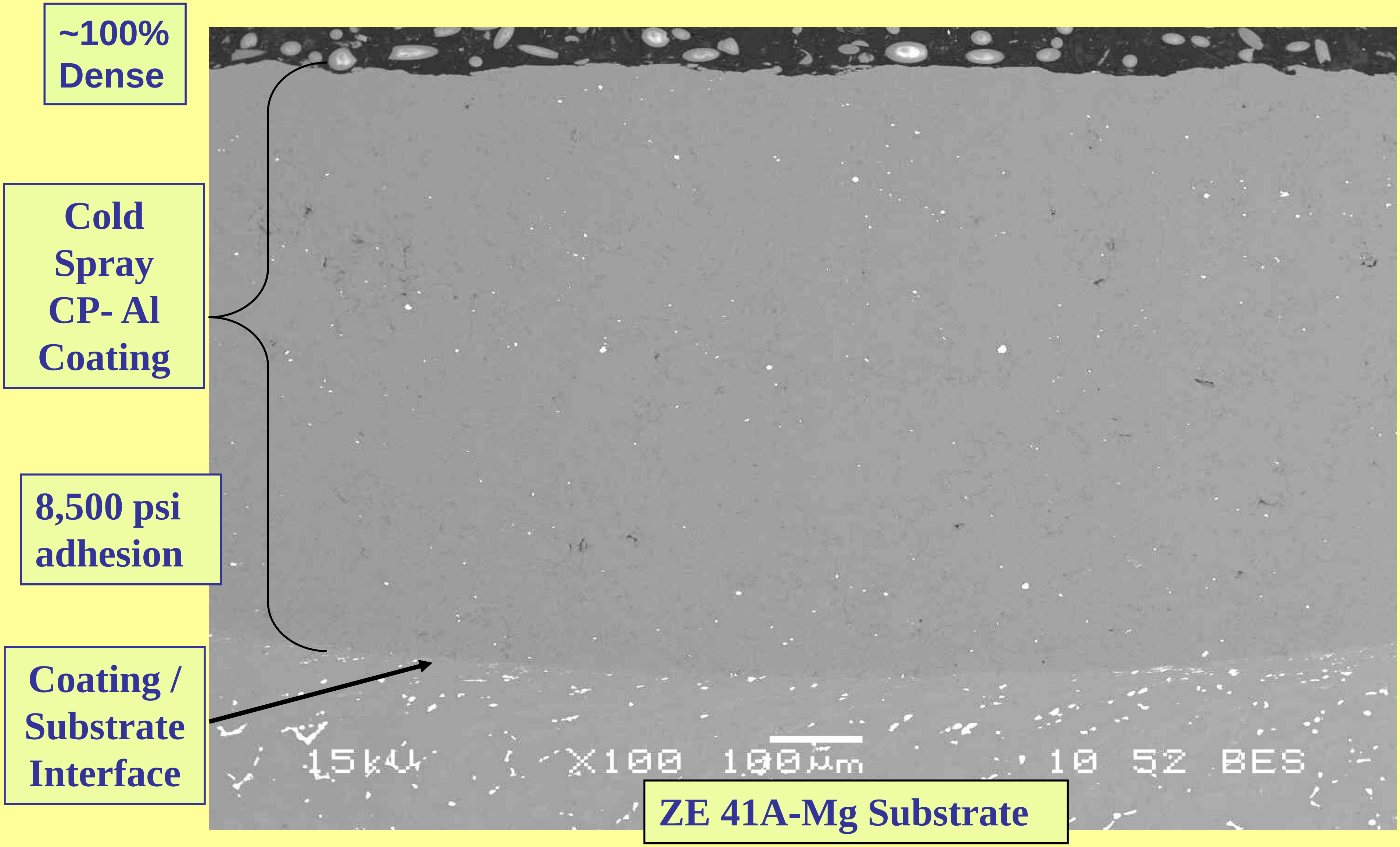
Particle Velocity Distribution Measured by DPV 2000



20 micron copper particles
25 mm downstream
400 psi, 400 C N_2 gas

Cold Spray Coating of CP-Al On ZE 41A-Mg

(Helium Carrier Gas)



ARL Technical Hurdle

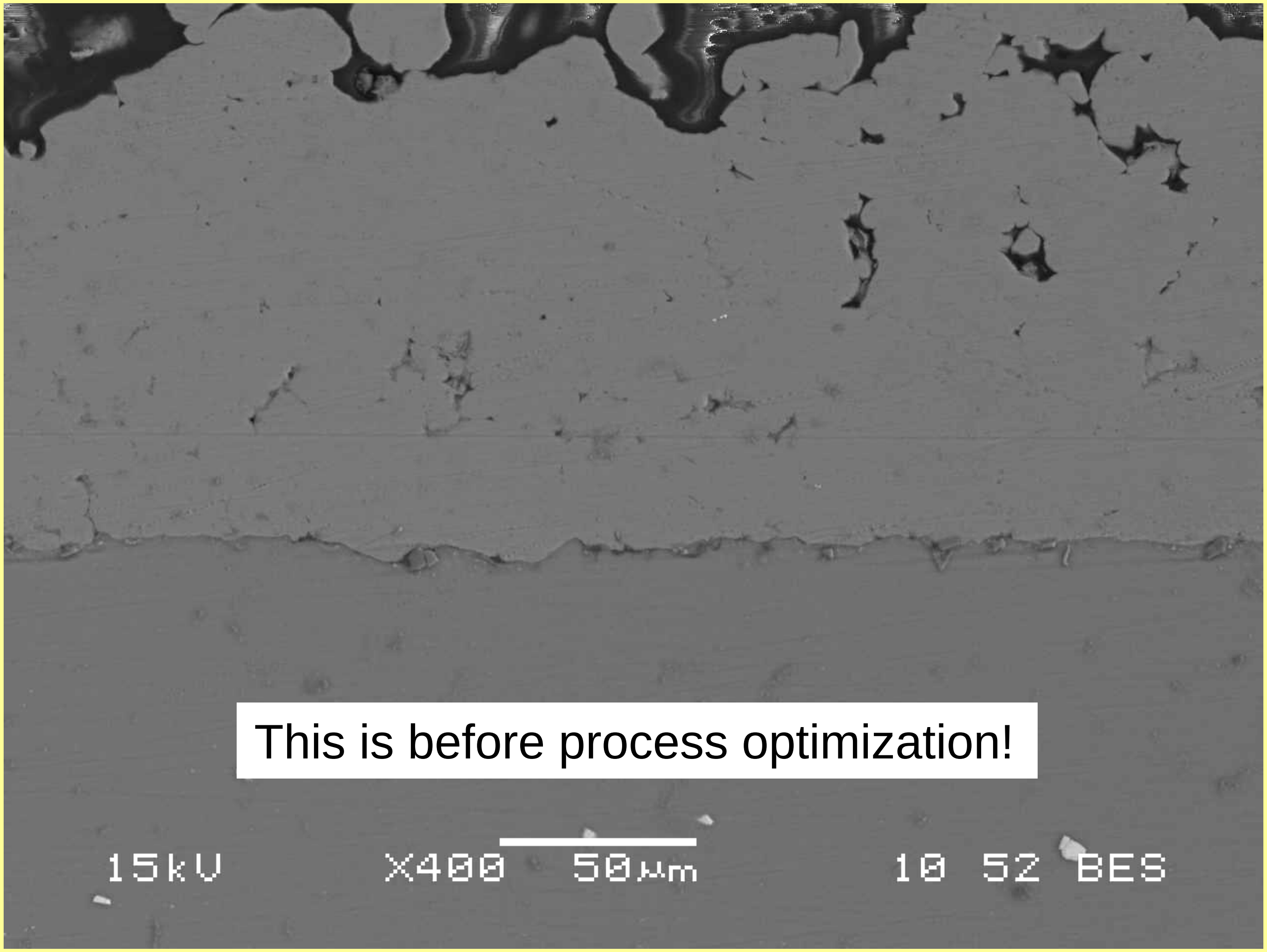
No Porosity & 8,500 psi bond strength using Helium

Achieve similar results with the use of nitrogen as the carrier gas

Technical Approach

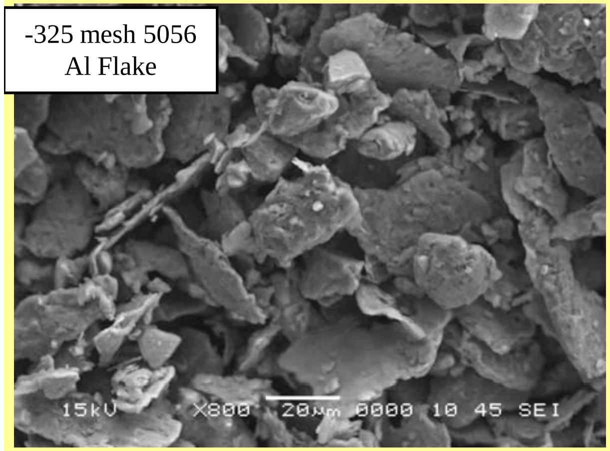
- **Nozzle – Material & Design**
- **Powder Size, Morphology**
- **Process Parameters**

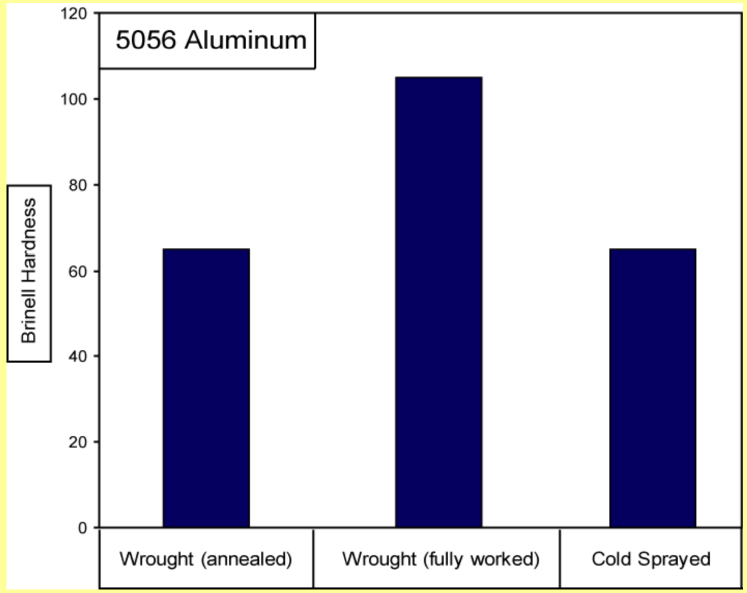
Cold Spray Coating of CP-Al on ZE41A-Mag (Nitrogen at 380 psi, 250 C)

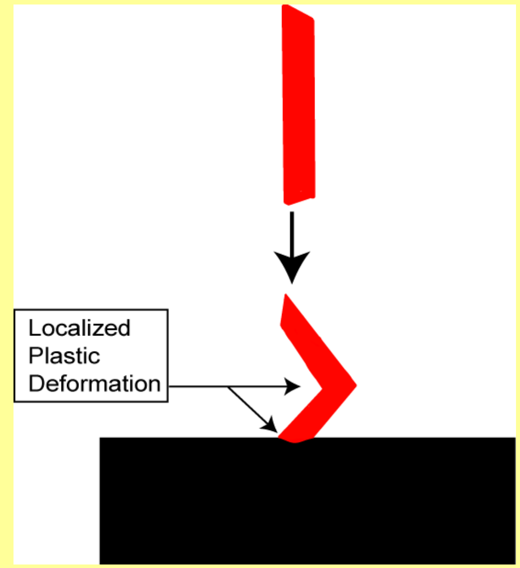


Aluminum Powder Morphology

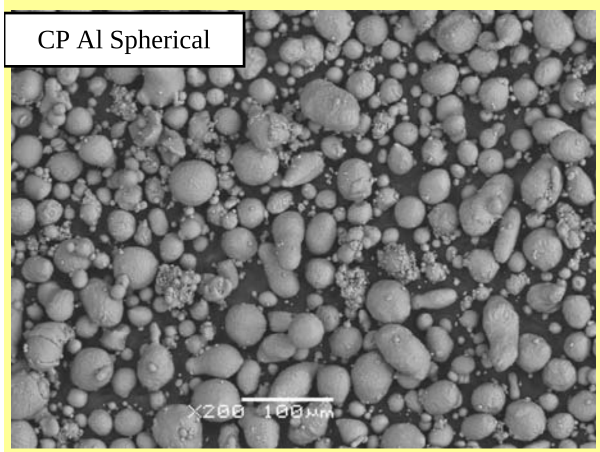
-325 mesh 5056 Al Flake

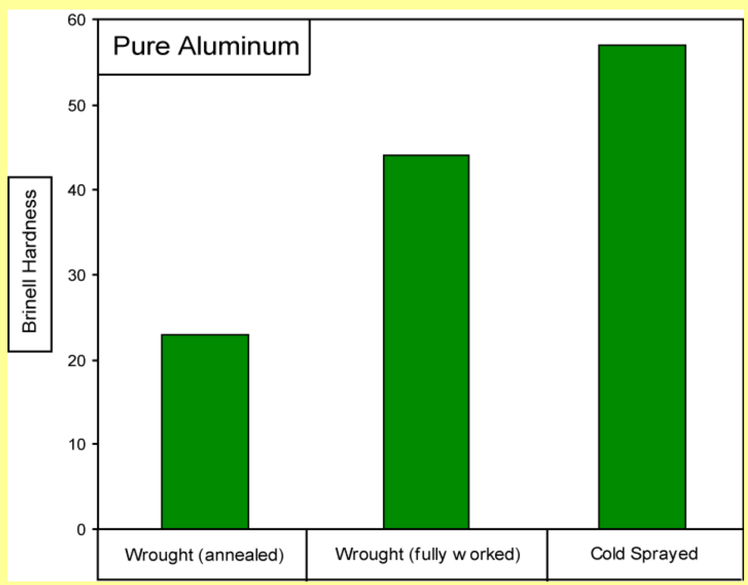


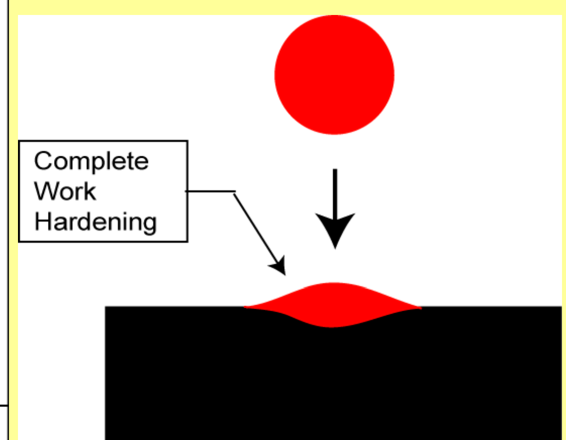




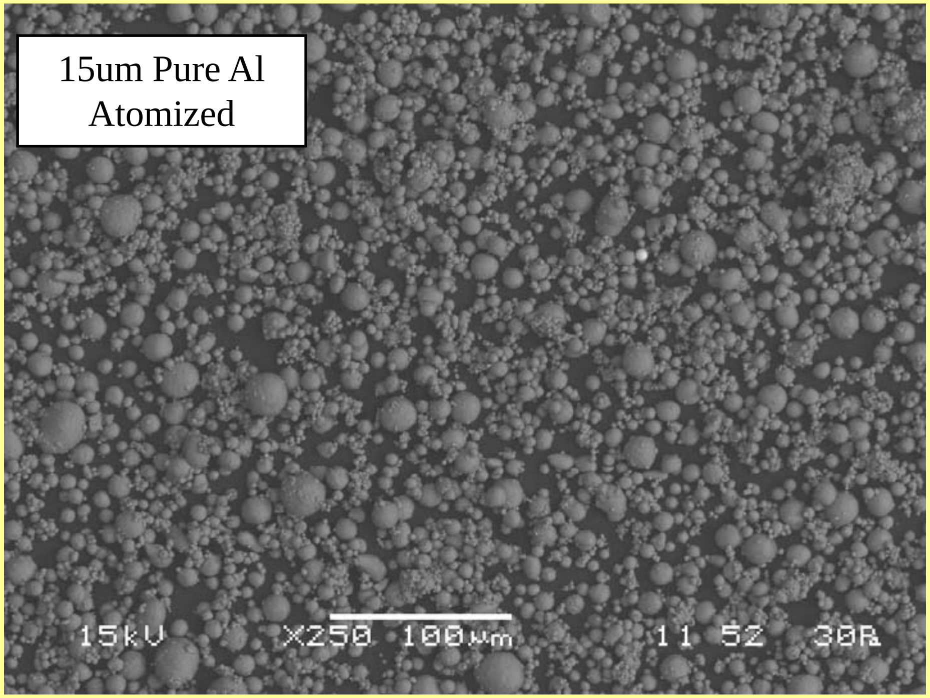
CP Al Spherical







Aluminum Powder Morphology

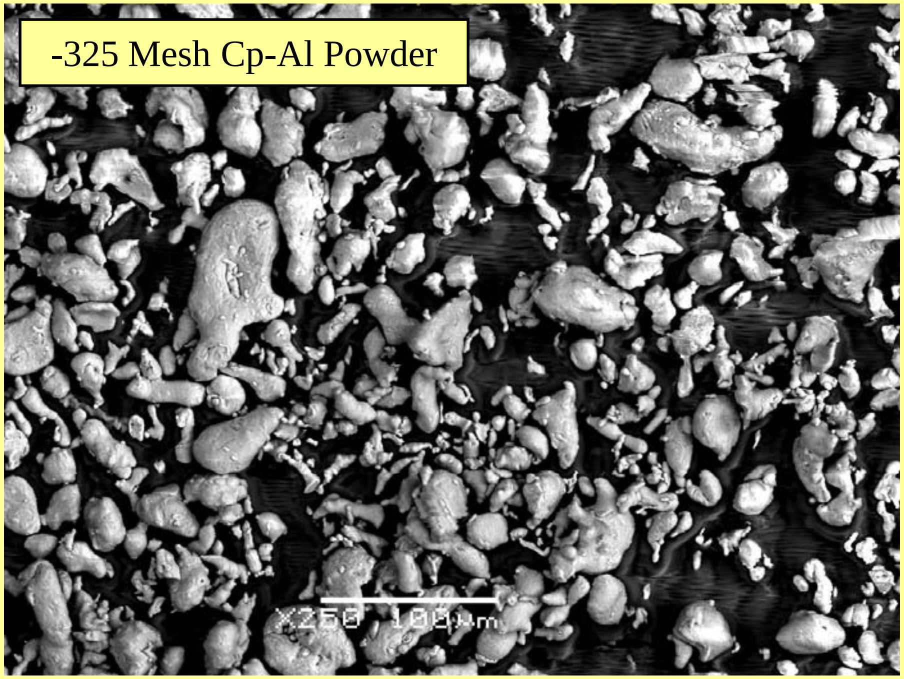


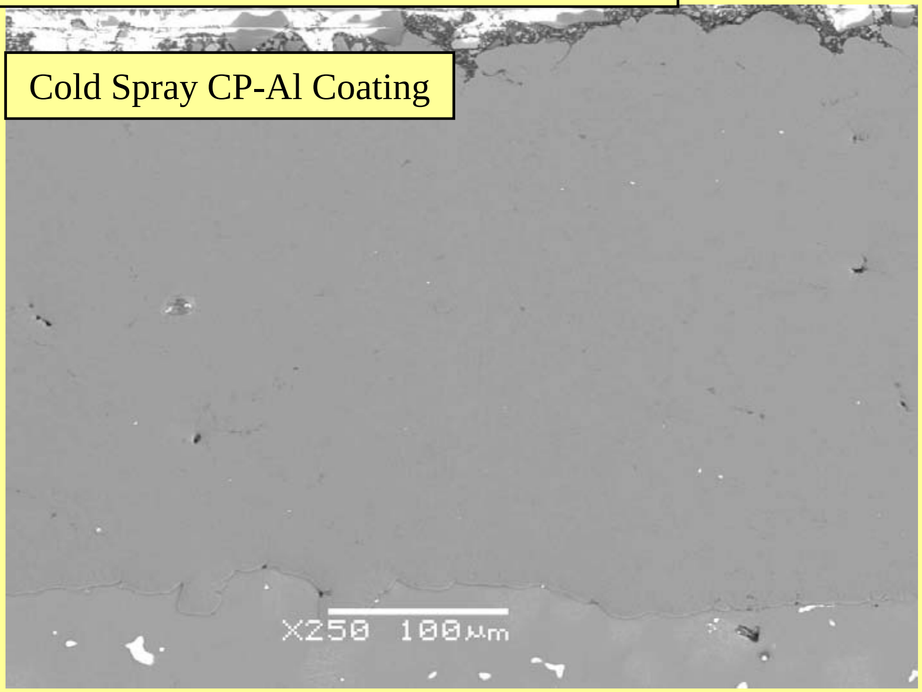
Coating quality is critically dependent on the feed powder composition, morphology, oxygen content, and mechanical properties.

Purity of Cold Sprayed Aluminum

Oxygen content measured by Inert Gas Fusion

ASTM E 1019-03





0.34 %Oxygen

0.25 %Oxygen

*The oxygen content of the cold spray coating is largely determined by the oxygen content of the original powder, not the process.

Modeling Efforts

Gasdynamic equations are used to calculate gas velocity and temperature within the nozzle and downstream of the nozzle exit.

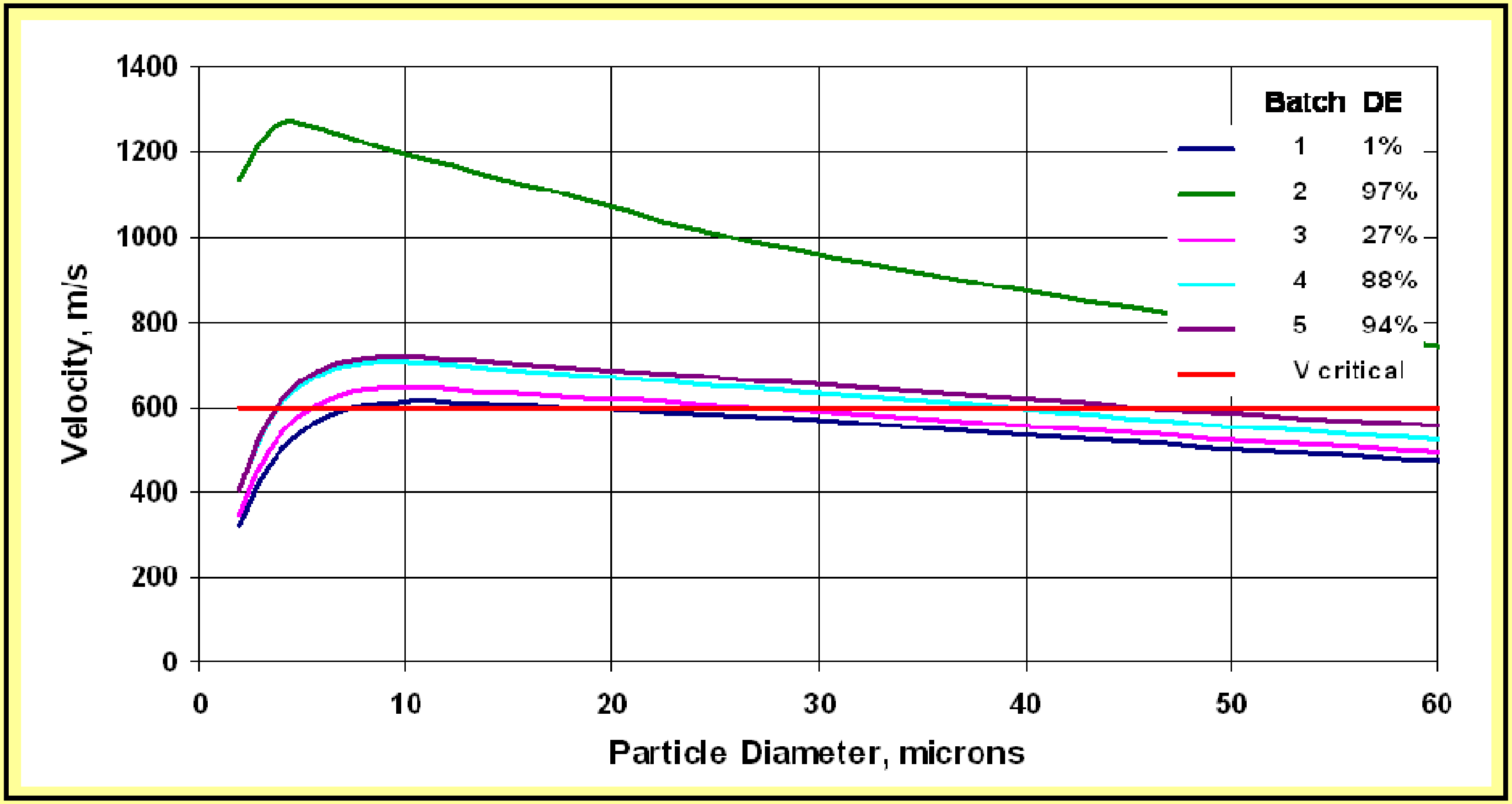
⇓

The resulting particle velocities and temperatures are then calculated by gas-particle drag and heat transfer.

⇓

The log normal particle size distribution is integrated from the smallest diameter to the largest diameter for those particles with velocities greater than the critical velocity, to determine DE.

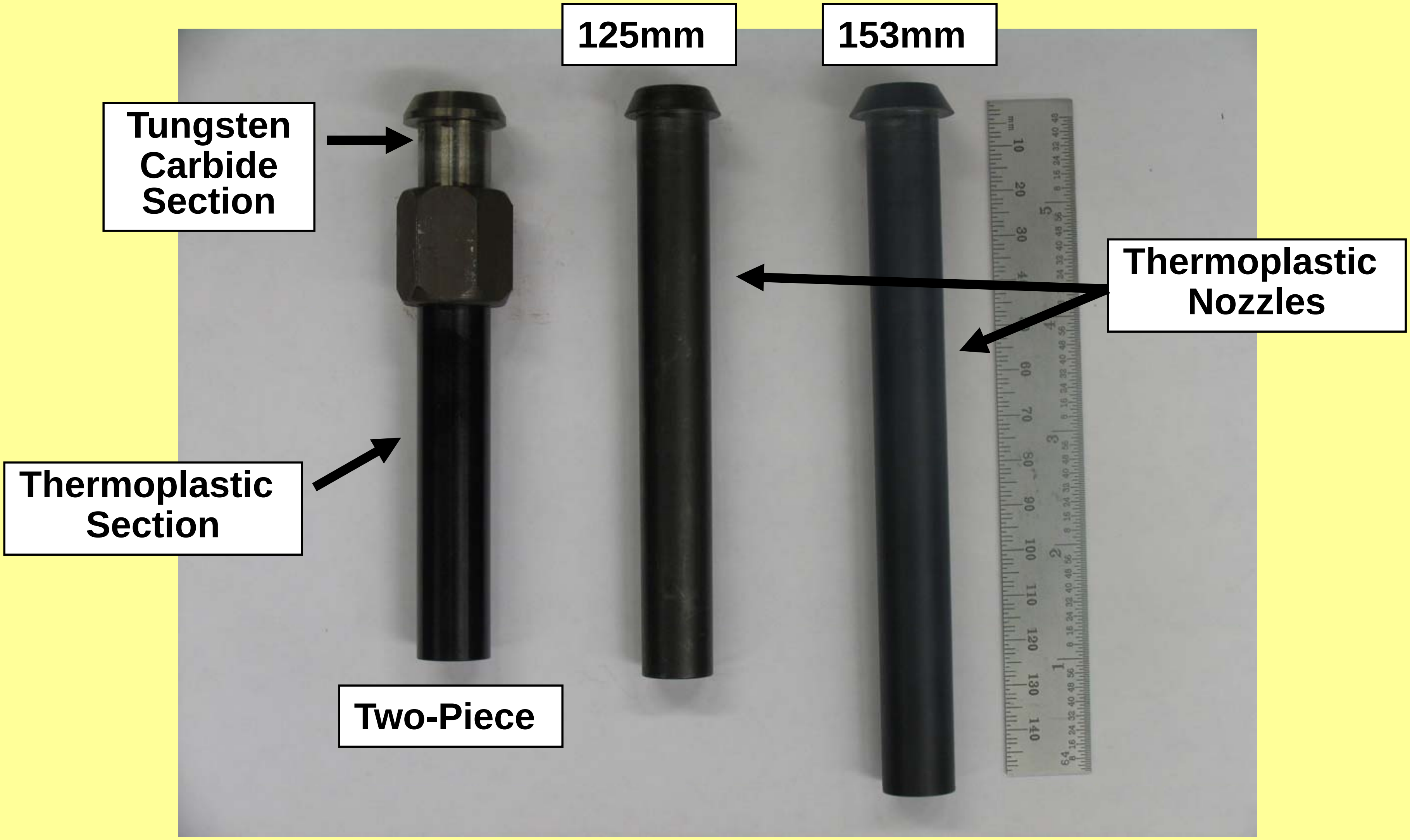
Particle Velocity & Deposition Efficiency



Nozzle Designs

Material	Length (mm)	Process Conditions	Particle Velocity
Tungsten Carbide	115	He, 380psi, RT	1020
Tungsten Carbide	115	N2, 380psi, 250C	590
WC/ Thermoplastic	115	N2, 380psi, 300C	605
Thermoplastic	125	N2, 380psi, 400C	690
Thermoplastic	153	N2, 380psi, 400C	710

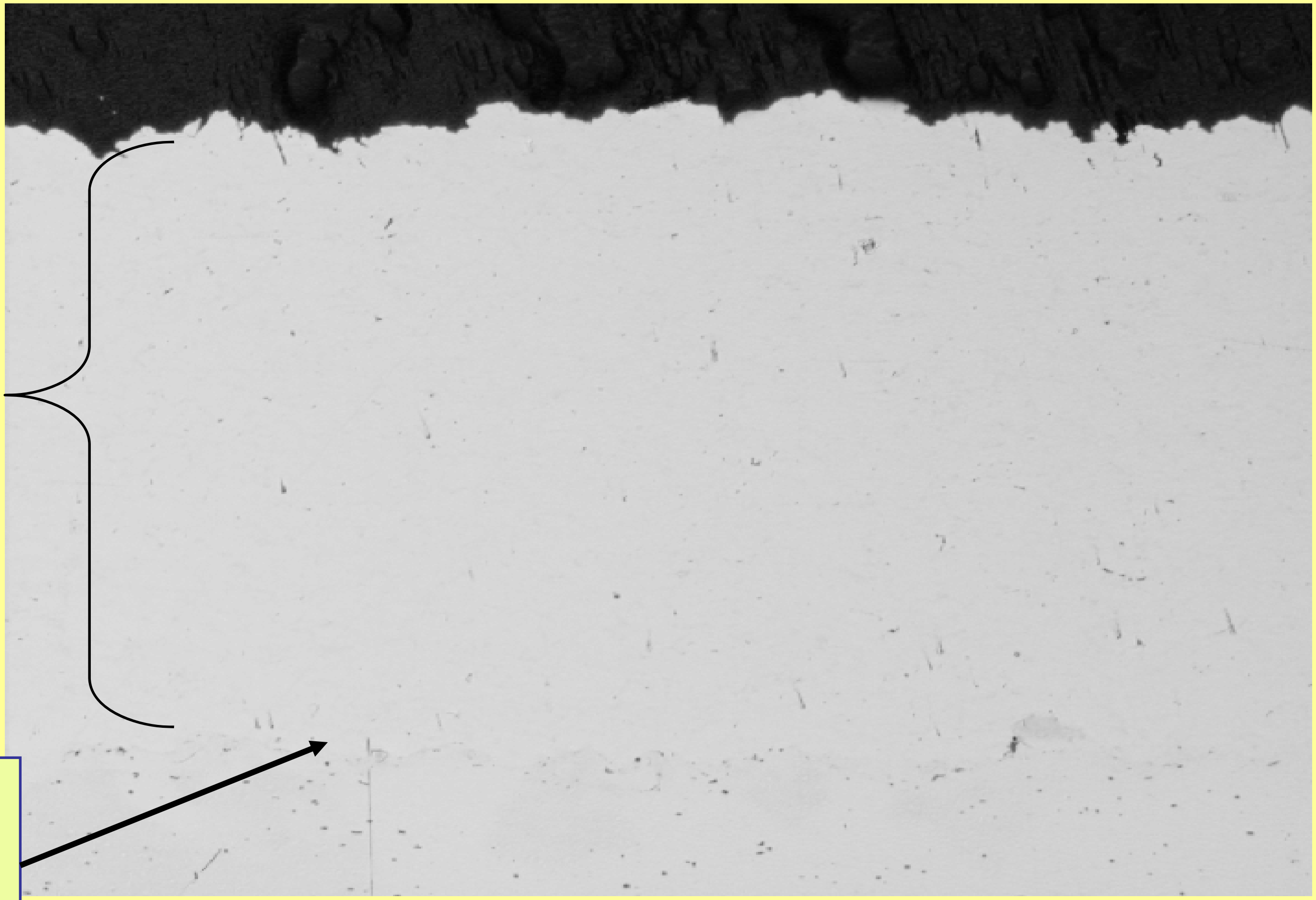
Thermoplastic Cold Spray Nozzles



Cold Spray Coating of CP-Al On ZE 41A-Mg

(Nitrogen Gas @ 400^0C)

Cold Spray CP- Al Coating



Coating / Substrate Interface

10,350 psi adhesion (ASTM C-633)

Bond Bar Adhesion Set-up

Bond Strength Measurements on ZE41A Magnesium and 7075 Aluminum Alloy

Bond Bar Adhesion Testing Setup

Results for CP- Aluminum Cold Spray Coatings on 6061 Aluminum Bond Bars

Process Conditions	*Nozzle Powder*	*Adhesion (psi)*
N2, 380psi, 250C	Metal 15- 45 um	2743
He, 380psi, 20C	Metal 15- 45 um	1657-3302
N2, 380psi, 300C	Metal/Plastic 7-28 um	2387-4476 (cohesive)
N2, 380psi, 400C	Plastic (125mm) 7-28 um	5787-7247 (cohesive)

Results for CP- Aluminum Cold Spray Coatings on Magnesium

Process Conditions	*Nozzle Powder*	*Adhesion (psi)*	*Corrosion Results*
N2, 380psi, 250C	Metal 15- 45 um	2743	8 hrs
He, 380psi, 20C	Metal 15- 45 um	>8,505 (glue failure)	>500 hrs*
N2, 380psi, 300C	Metal/Plastic 7-28 um	4764-5985	1000 hrs
N2, 380psi, 400C	Plastic 7-28 um	>10,350 (glue failure)	>2,400 hrs*

* Failure of Edge Maskant

Salt Spray (Fog) Corrosion Test (ASTM B-117)

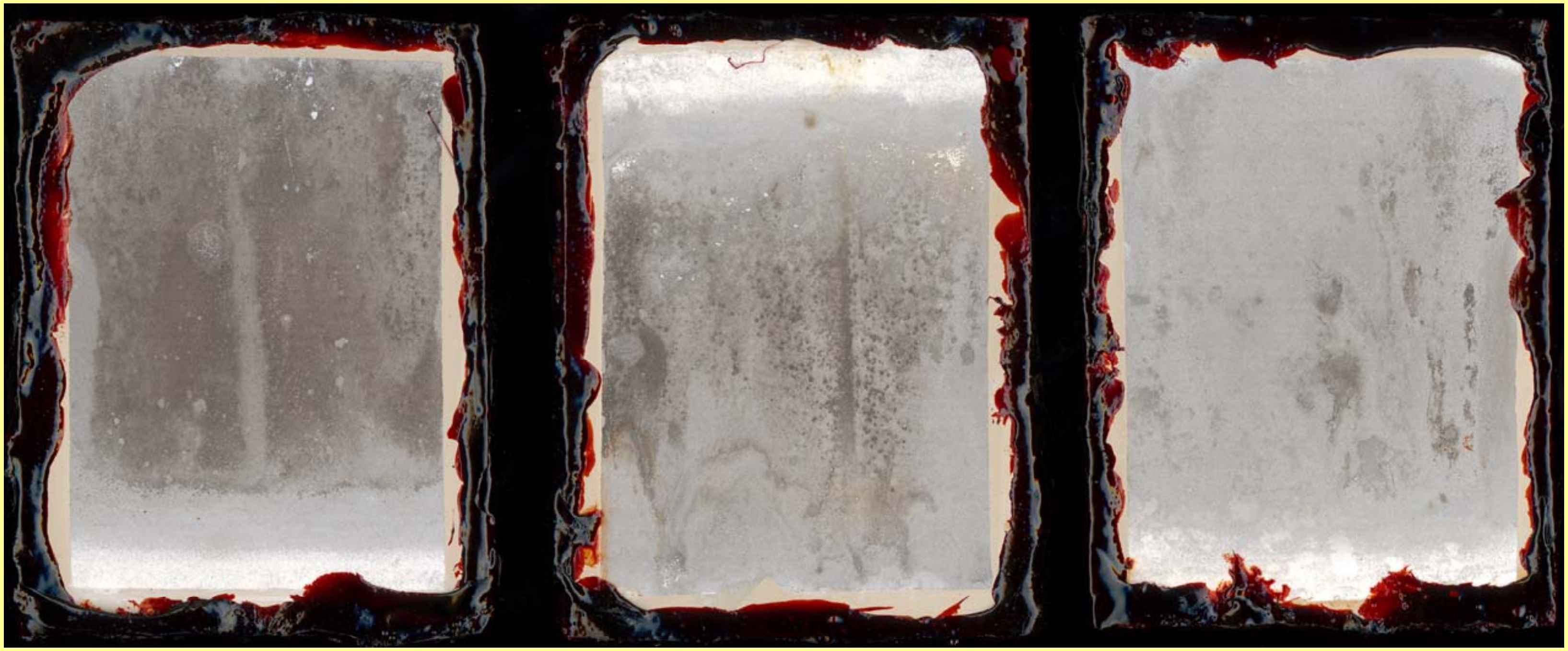
- Specimens at 15-30^{0} angle from vertical
- 5 +/- 1% (by weight) NaCl Solution (pH 6.5-7.2)
- Spray Nozzle Baffled at 10-25psi
- Chamber Temperature at 35 + 1.1 – 1.7 ^{0}C
- Continuously sprayed in closed chamber

Note: No Direct Relation between B117 & Outdoor Exposure

Aluminum coated ZE41A Magnesium (8 Hours in Salt Spray)

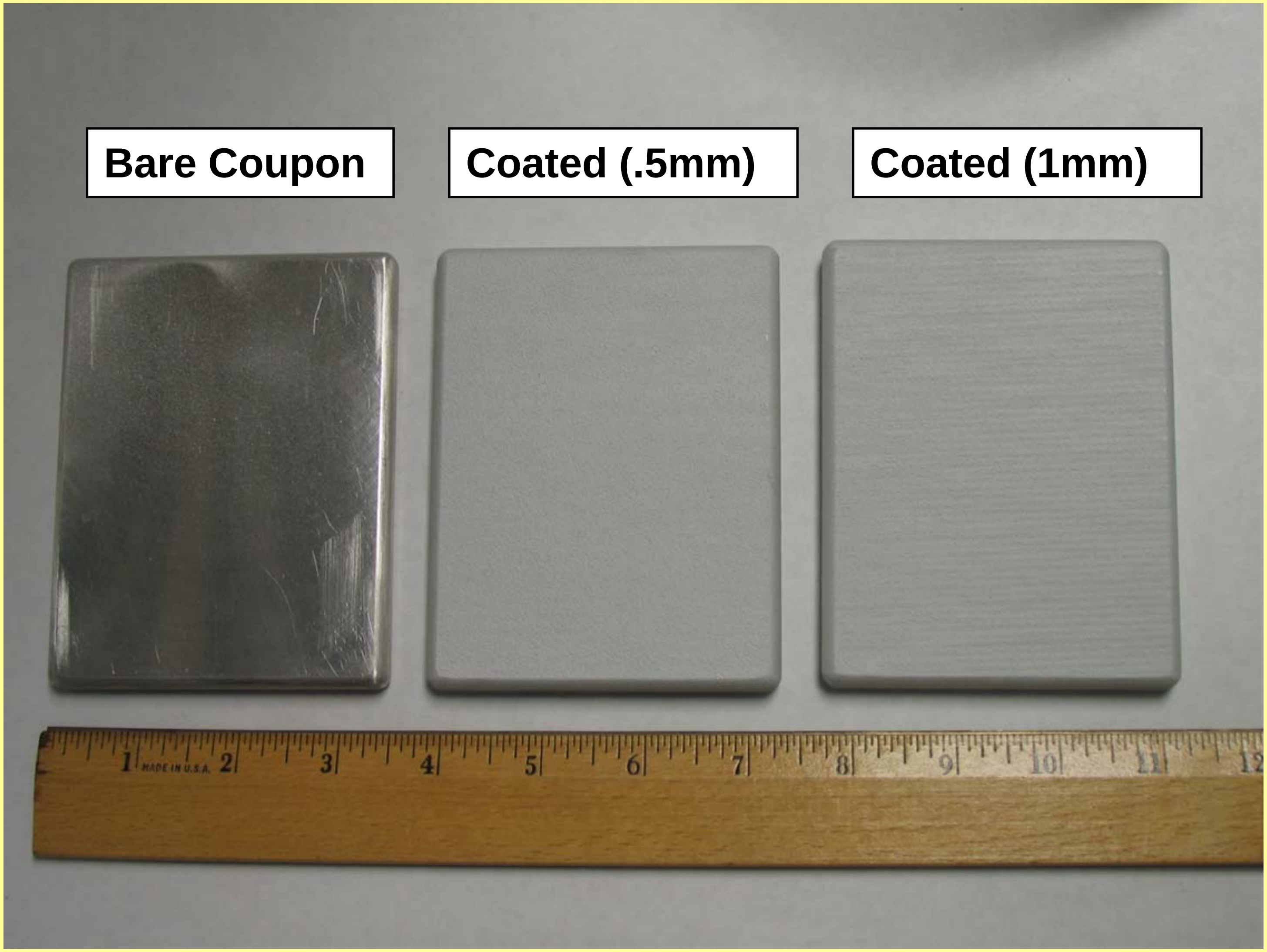
Cold Spray Aluminum deposited using N_2 Gas at 250 ^{0}C

Aluminum coated ZE41A Magnesium (336 Hours in Salt Spray)



Cold Spray Aluminum deposited using Helium Gas at 20 ^{0}C

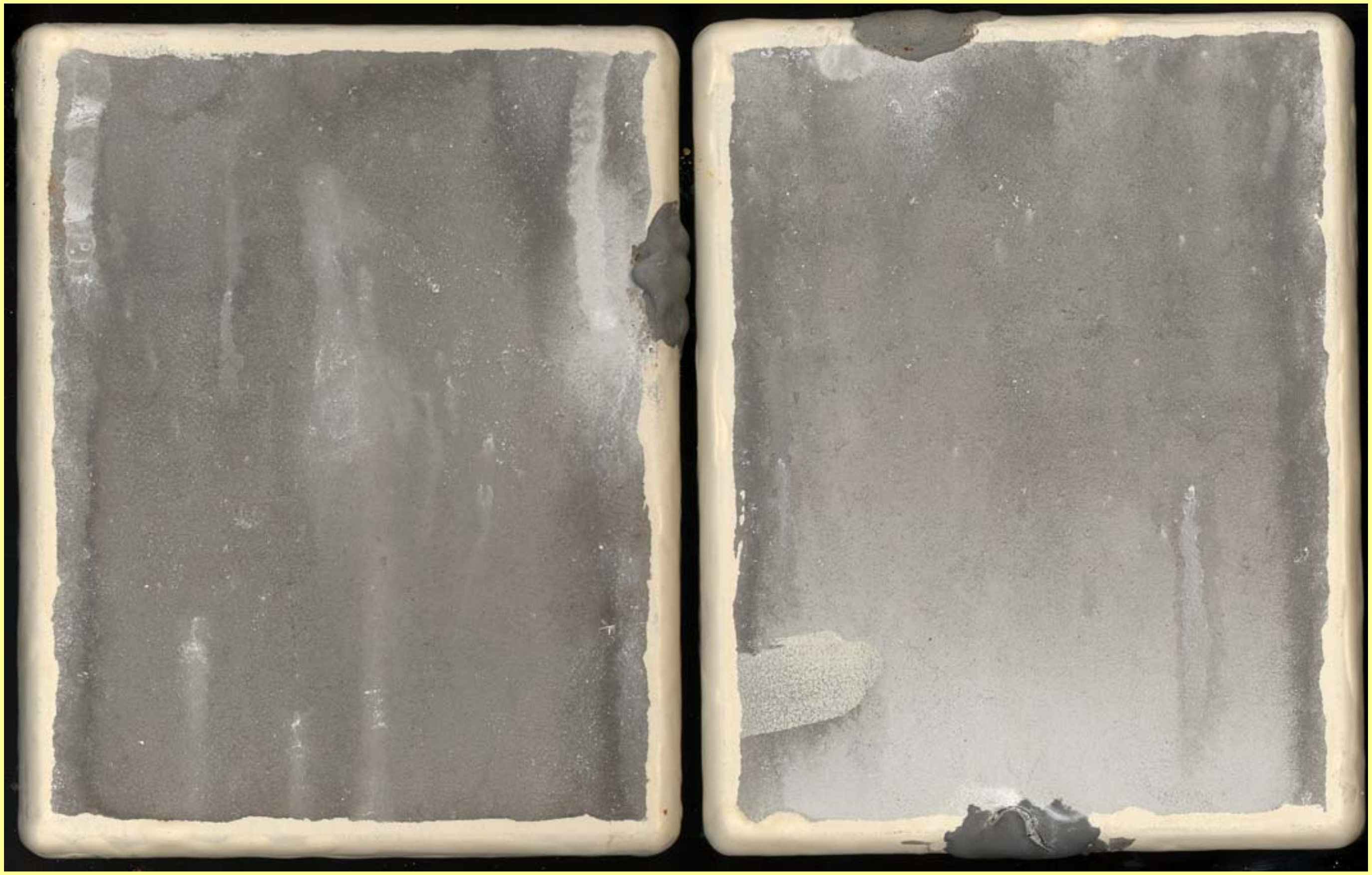
Cold Spray Aluminum coated ZE41A Magnesium Coupons



Aluminum Cold Spray Coated Magnesium Coupons After Salt Spray Exposure

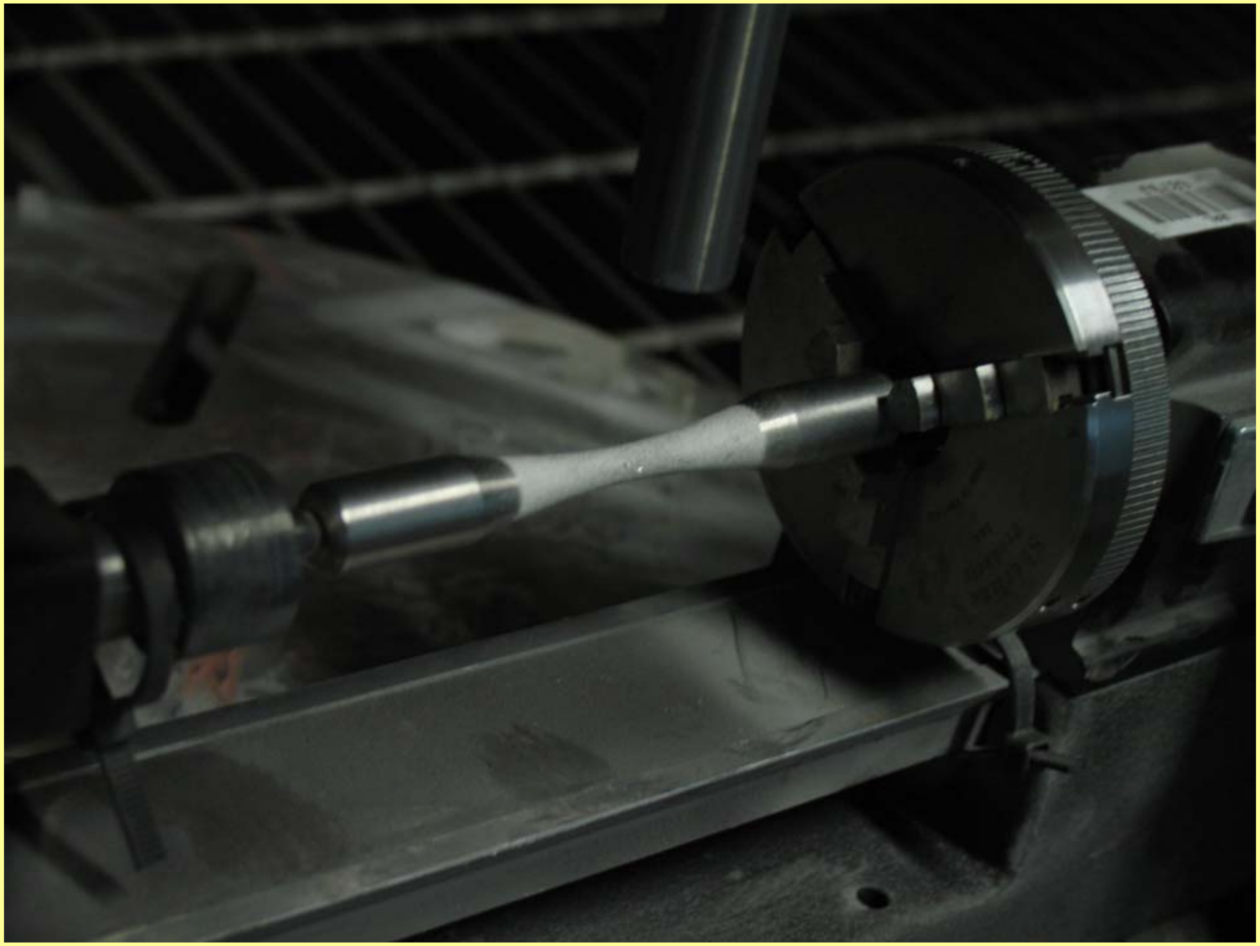
2400 Hours Exposure (.5mm)

2400 Hours Exposure (1mm)



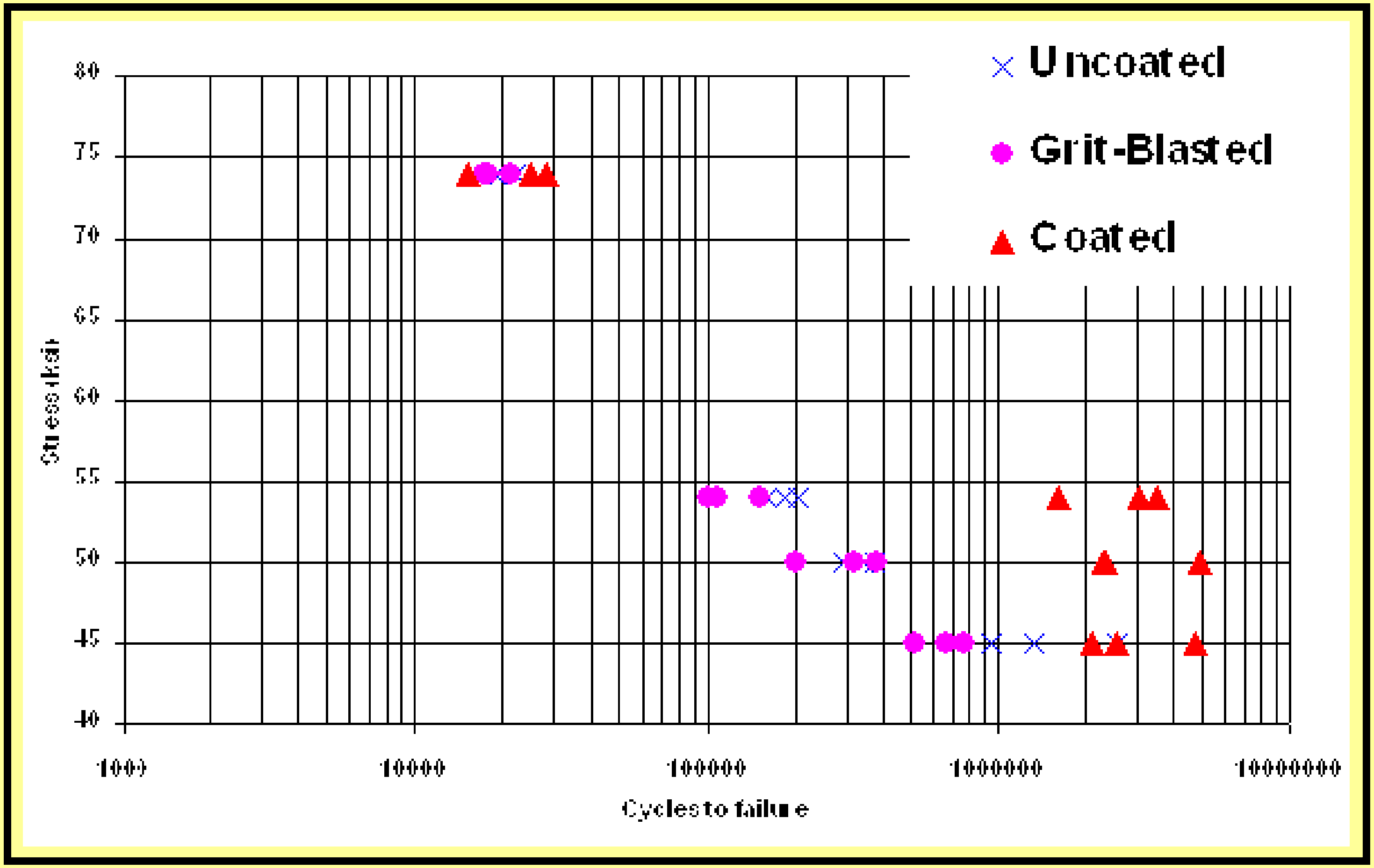
Cold Spray Aluminum deposited using N_2 Gas @ 400 ^{0}C

RCB Cold Spray Set-Up



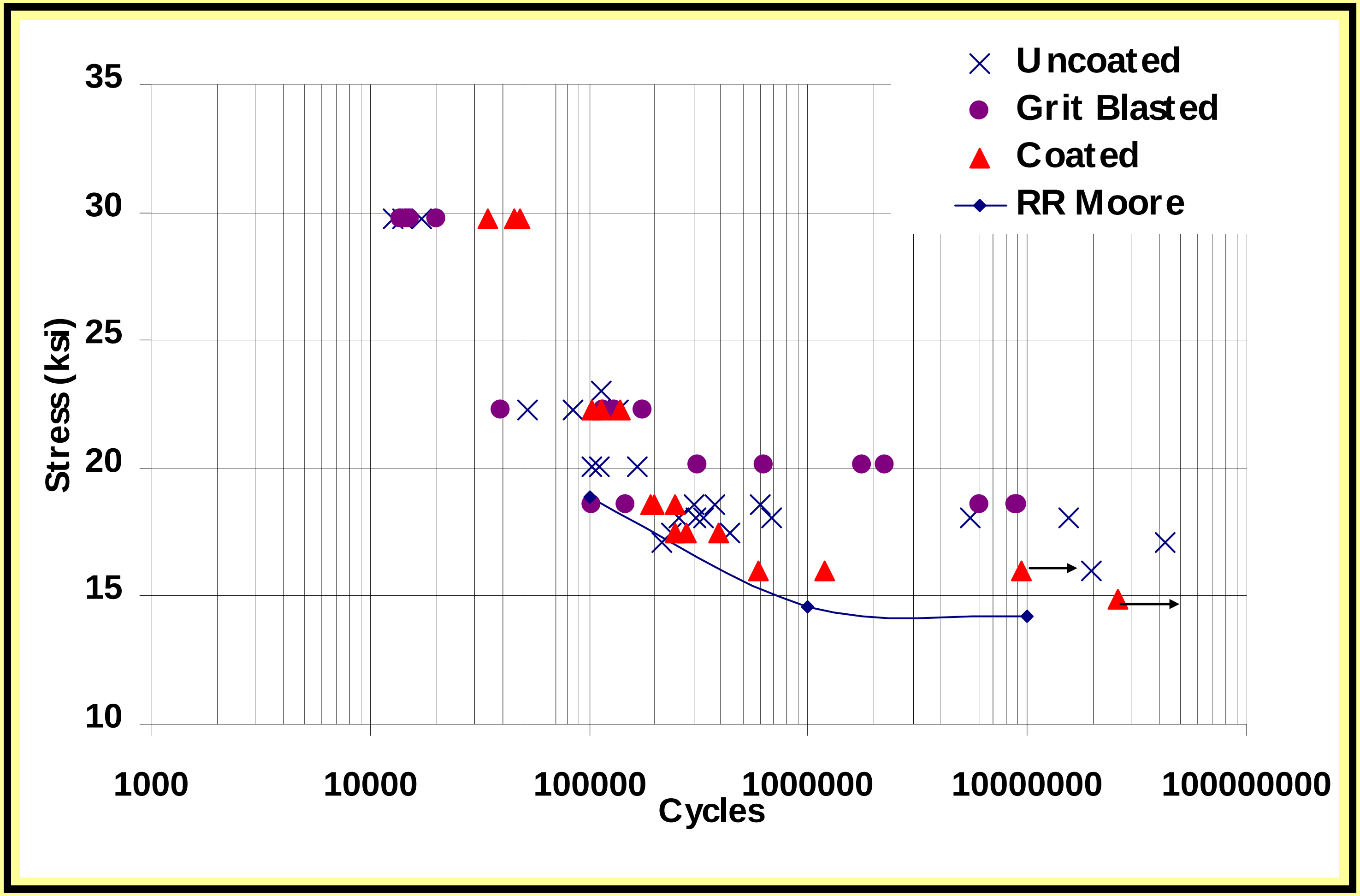
ZE41A Magnesium & 7075 Aluminum Alloy RR Moore Fatigue Specimens

Fatigue Results – AA7075-T651



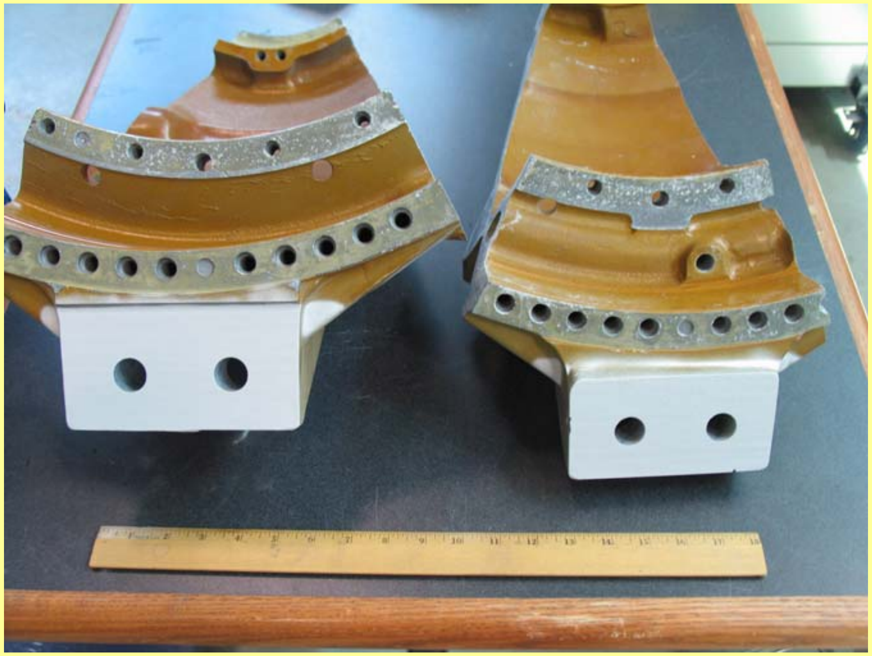
Source – Australian Defence Science & Technology Organisation

Fatigue Results – ZE41A-T5



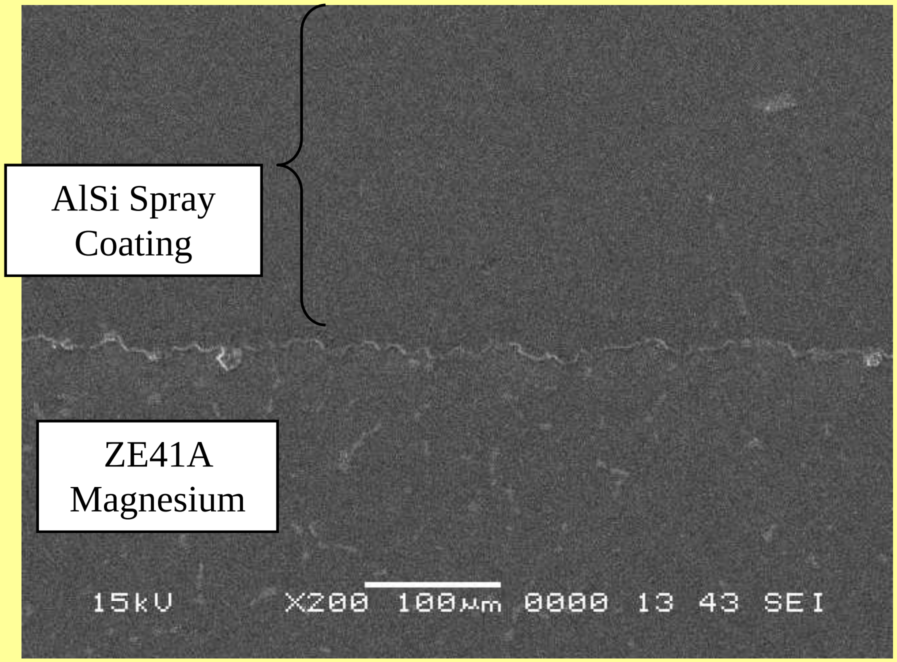
Source – Australian Defence Science & Technology Organisation

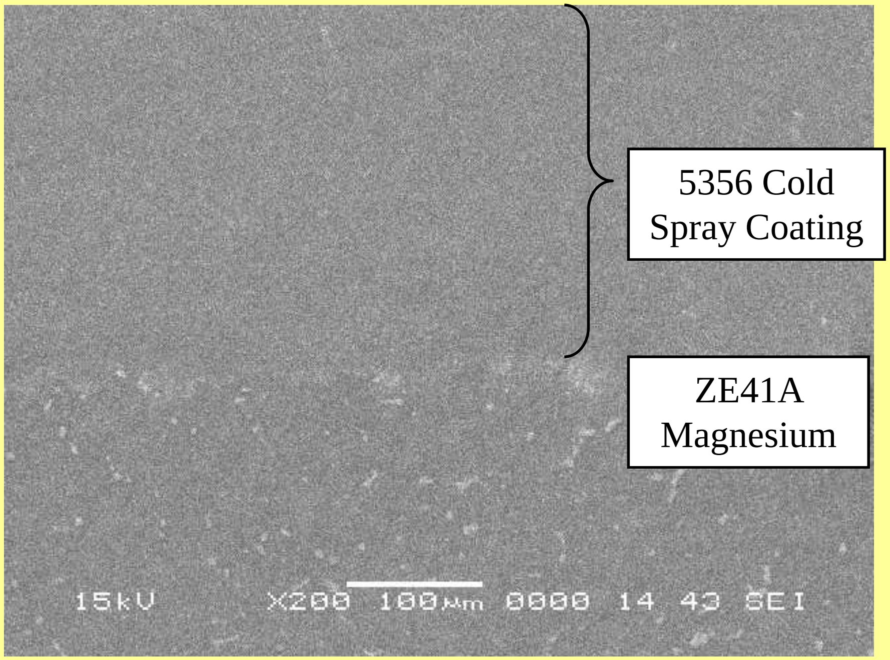
Mg Housing Coated with CP-Al



Flat surface of Mg housing covered with CP-AL Cold Spray

Al12Si & 5356 Al Deposited on ZE41A Using Helium





Adhesion Results - > 8,000 psi (Glue Failure)

Summary

Achieved High Density, Low Porosity Cold Spray Aluminum Coating

Bond Strength Exceeds 10,000 psi.

Corrosion Resistance exceeds 2500 hours B117 Salt Fog Spray

No Reduction in Fatigue Strength on Magnesium

Slight fatigue credit on 7075 Aluminum Alloy

Future Work – Investigate Aluminum Alloys & High Purity Aluminum